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OFFICE OF NAVAL RESEARCH
Contract N00014-K-0258
Technical Report No. 5

Atomic Force Microscopy and Scanning Tunneling Microscopy with a Combination Atomic Force Microscope/Scanning Tunneling Microscopy

O. Marti, B. Drake, S. Gould and P.K. Hansma
Department of Physics
University of California
Santa Barbara CA 93106

Prepared for Publication in

J. Vac. Sci. Technol., to appear

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	
1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
3. DISTRIBUTION / AVAILABILITY OF REPORT	Approved for Public Release; Distribution Unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5
5. MONITORING ORGANIZATION REPORT NUMBER(S)	
6a. NAME OF PERFORMING ORGANIZATION	Department of Physics, UC Santa Barbara, CA 93106
6b. OFFICE SYMBOL (If applicable)	
7a. NAME OF MONITORING ORGANIZATION	Office of Naval Research
6c. ADDRESS (City, State, and ZIP Code)	Department of Physics, University of California, Santa Barbara, CA 93106
7b. ADDRESS (City, State, and ZIP Code)	Department of the Navy, 800 N. Quincy Street, Arlington, VA 22217
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	Office of Naval Research
8b. OFFICE SYMBOL (If applicable)	
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	Contract No. N00014-K-0258
8c. ADDRESS (City, State, and ZIP Code)	Department of the Navy, 800 N. Quincy Street, Arlington, VA 22217
10. SOURCE OF FUNDING NUMBERS	PROGRAM ELEMENT NO / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO
11. TITLE (Include Security Classification)	Atomic Force Microscopy and Scanning Tunneling Microscopy with a Combination Atomic Force Microscope/Scanning Tunneling Microscope
12. PERSONAL AUTHOR(S)	O. Marti, B. Drake, S. Gould and P.K. Hansma
13a. TYPE OF REPORT	Technical
13b. TIME COVERED	FROM ____ TO ____
14. DATE OF REPORT (Year, Month, Day)	1988 June
15. PAGE COUNT	
16. SUPPLEMENTARY NOTATION	

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
STM
AFM
interchangeable heads

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Since almost all the electronic and mechanical requirements for an atomic force microscope (AFM) are the same as for a scanning tunneling microscopy (STM), it is convenient and practical to build a combination AFM/STM with interchangeable heads. The conversion from one to the other can be made in a few minutes. Representative images demonstrate that atomic resolution can be obtained in both modes of operation. With the two modes of operation, it can image conductors, semiconductors, and insulators.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT	[X] UNCLASSIFIED/UNLIMITED [X] SAME AS RPT. [ ] DTIC USERS
21. ABSTRACT SECURITY CLASSIFICATION	Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	Dr. David L. Nelson
22b. TELEPHONE (Include Area Code)	(202)696-4410
22c. OFFICE SYMBOL	

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

687803JVA = 687803JVA

Running Title: AFM and STM with a combination AFM/STM

Atomic force microscopy and scanning tunneling microscopy with a combination atomic force microscope/scanning tunneling microscope

O. Marti, B. Drake, S. Gould, and P. K. Hansma

Department of Physics, University of California, Santa Barbara, California 93106

(Received 2 November 1987; accepted 29 December 1987)

Since almost all the electronic and mechanical requirements for an atomic force microscope (AFM) are the same as for a scanning tunneling microscopy (STM), it is convenient and practical to build a combination AFM/STM with interchangeable heads. The conversion from one to the other can be made in a few minutes. Representative images demonstrate that atomic resolution can be obtained in both modes of operation. With the two modes of operation, it can image conductors, semiconductors, and insulators.

Scanning tunneling microscopy (STM) is rapidly becoming a mature field, even though fewer than ten years have elapsed since its discovery.[1] Already there have been a number of review articles published,[2-5] and several companies[6-8] now offer commerical STM's for sale. Basically, the STM lowers a metal tip to ~0.5 nm from a surface. At this point electrons can tunnel from the tip to the surface. The tunneling current depends strongly on the distance between the tip and the surface. For example, this current can change by an order of magnitude for a change in distance of only one atomic diameter. By moving the tip across the surface while raising and lowering it to keep this current constant the STM accurately traces contours as small as a fraction of an atomic diameter.

Atomic force microscopy[9-14] (AFM) is similar to scanning tunneling microscopy in many respects. The images consist of a series of parallel profiles of a surface. Each profile is obtained by moving a tip, which is ideally terminated by a single atom, across the surface with a very small tracking force: of order 10^{-8} N. Predecessors of this instrument include profilometers,[15-17] the topografiner,[18] and STM's.[1-8] The AFM, unlike the STM, is not restricted to conductive or semiconductive surfaces. Atomic resolution imaging has been demonstrated with AFM's[10-12] approaching the resolving power of STM's and being much better than that of the stylus profilometers. This paper will focus on the key elements of three designs that we have built and tested.

Our basic AFM design is an extension of an earlier STM design[19] and an improved version of the first operational AFM design[12] by our group. The main parts of our microscope are described in Fig. 1. The sample is mounted on an x,y,z scanner[20] and pressed against a tip mounted on a spring. The deflection of the spring is monitored by sensing the tunneling current between the back of the spring and a sensing electrode.

This AFM can be converted to an STM by simply replacing the top piece with a rigid tip holder and sensing the tunneling current between this rigidly held tip and the sample. Most of the electronics are common to both instruments. In each case the feedback circuitry keeps a tunneling current constant by changing the z position of the sample as it is scanned in an x,y raster under the tip. The only difference is that for the STM the tunneling occurs between the tip and the sample while for the AFM the tunneling occurs between the back of the spring and a sensing electrode.

Figure 2 shows the single-tube x,y,z scanner that we now use. It is 1.9 cm long and 1.3 cm in diameter. The active length, that is, the length above the Macor mounting plate is ~1.3 cm. Note that the longitudinal and transverse resonant frequencies of 60 and 36 kHz, respectively, are large enough to make the scanner relatively immune to external vibrations. Specifically, consider a vibration at a frequency ν, very much less than the resonant frequency ν_R of the scanner. The variation in the position of the sample relative to the mounting holes of the Macor will be approximately the amplitude of the driving vibration times (ν/ν_R).[2] For example, for a vibration with an amplitude of 10 μm at 20 Hz the sample will move $< \frac{1}{10}$ Å relative to the mounting holes for the scanner shown in Fig. 2.

The key part of an atomic force microscope is the sensor assembly. We have tried three different designs, each of which has given atomic resolution. The rest of this manuscript will discuss these three types with their advantages and disadvantages.

The first type we tried is the double cross shown in Fig. 3. For this force sensor the tip, which was a fragment of a shattered diamond, is glued to a spring that is formed by a double

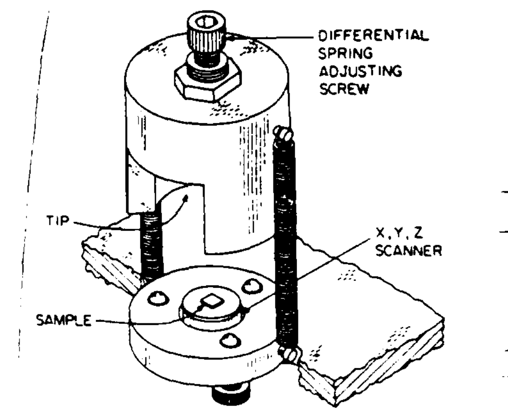

FIG. 1. Setup of the atomic force microscope (AFM). The base plate holds the x,y,z scanner and the sample, while the top part contains the tip which is a component part of the force sensor. In operation the top part is supported on three screws through the base plate. These screws are turned to gently lower the tip down to the sample.

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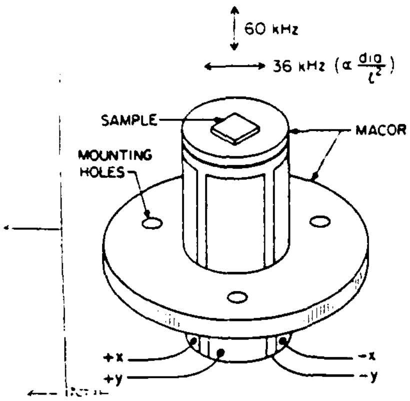

FIG. 2. A single-tube scanner with the sample mounted on the central axis, the four outside the electrode driven symmetrically with $+x$ and $-x$, $+y$ and $-y$, and the inner electrode driven with z shows good orthogonality of the x, y, and z axes.

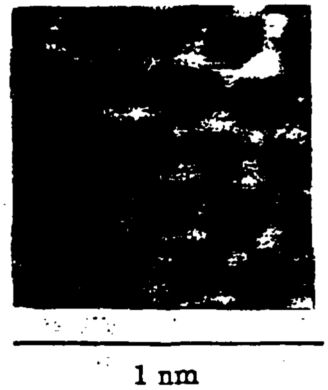

FIG. 4. This image of graphite was taken with an AFM based on the double cross shown in Fig. 3.

cross of fine wire. The deflection of this spring was sensed by the tunneling current from the spring to a sensing electrode above it. The fine mechanical adjustment above the double cross was done with the differential spring adjusting screw shown in Fig. 1. Basically, the differential spring consisted of a coil spring in a Teflon-lined cavity. One end of the spring rested against the differential spring adjusting screw, which could be turned to compress the spring. The other end of the spring was a lever on which the sensing electrode was mounted. We found that a ratio of spring constants in the range 1:1000 is appropriate. Then, for example, as the spring is compressed 0.1 mm by the differential spring adjusting screw the sensing electrode moves 0.1 mm/1000 = 100 nm.

Figure 4 is an image of graphite taken with an AFM with a double cross.[12] The platinum wires that formed the double cross a diameter of 25 μm and an unsupported length of 4 mm giving a spring constant of $\sim$40 N/m. This image is a computer processed version of the original image[12] which was distorted because of nonorthogonality in the two electrode x,y scanner that we were using at that time.

Figure 5 shows our next successful design. This design was based on the SiO_2 microcantilevers[10] that were kindly supplied to us together with instructions for their use by Tom Albrecht and Calvin Quate. In this case, the sensing electrode was a loop of 20-μ-diam gold plated tungsten wire.[21] One purpose of having this loop of fine wire as the sensing electrode is that it decreases breakage of the microcantilevers if they are accidentally pushed hard against the sensing electrode. With this design we were able to image organic monolayers prepared by H. Ribi. Figure 6 is an image of a polymerized monolayer of 1-ethylenediaminotricosa-10,12-diynoicamide (attached to a glass slide) taken with an AFM with a SiO_2 microcantilever.[13] The spring constant of the microcantilever was ≈ 1 N/m and the applied force was $\approx 10^{-8}$ N. Details of the sample preparation and imaging conditions can be found in Ref. 13.

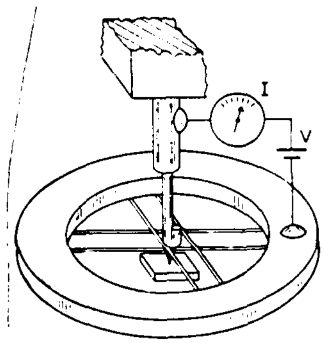

FIG. 3. The tunneling currents between a sensing electrode and double cross of fine wires can be used to sense the deflection of that double cross as the diamond, shown in black, presses against the rectangular sample. Thus the double cross can be used as the spring for an AFM.

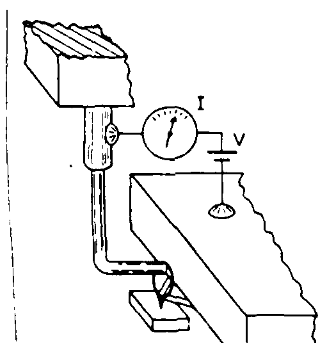

FIG. 5. An SiO_2 microcantilever can be etched from a silicon wafer (Ref. 10) and used as the spring in an AFM.

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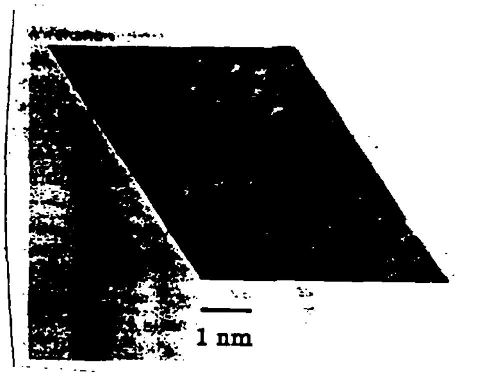

FIG. 6. This image of a polymerized monolayer of organic molecules was taken with an AFM based on the SiO_2 microcantilever shown in Fig. 5.

Finaly, Fig. 7 shows the most recent design in our laboratories. This is a double-wire antilever made with the same 20-μ-diam gold plated tungsten wire[21] mentioned previously. The purpose of the double cantilever is to increase the lateral spring constant compared to the vertical spring constant. This is a key feature that must be present in any AFM design. For this design the sensing electrode is a platinum iridium alloy wire ~ 0.1 mm in diameter. The length of each leg of the double cantilever can be changed to change the spring constant.

Figure 8 is an image of a silicon wafer that had been in our laboratory for over four years. The image was taken with an AFM with a double-wire cantilever.[22] Each leg was ~ 1.4 mm long which gave a spring constant of ~ 70 N/m. We were surprized to see the atomic scale features of this wafer with its "native oxide" from long exposure to room-temperature air. These features were aligned along (110)-type direction on the Si(111) wafer. Imaging was done with a tracking force $\simeq 10^{-9}$ N.

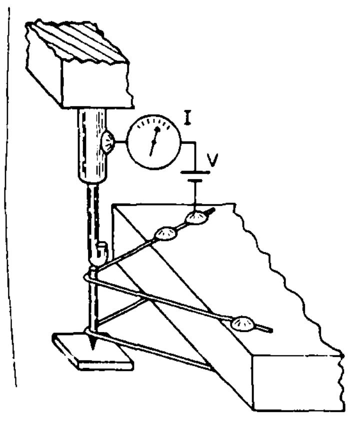

FIG. 7. A double-wire cantilever is relatively easy to fabricate and use.

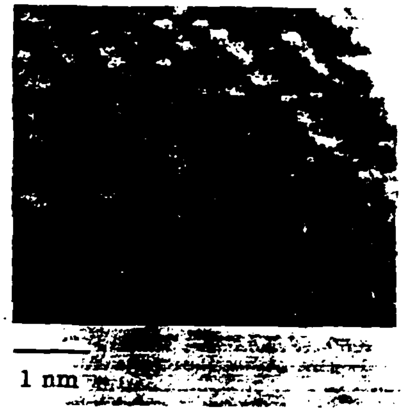

FIG. 8. This image of a silicon wafer was taken with an AFM based on the double-wire cantilever shown in Fig. 7.

Each design has its own advantages and disadvantages. The double cross is very stable laterally and robust but the most temperature sensitive of the three designs. Perhaps this is because small changes in the size of the ring that supports the double cross change the tension in the wires of the cross or partly straighten our minute kinks.

The SiO_2 microcantilevers combine high resonant frequency with low spring constants. For example, they can have resonant frequencies of order 100 kHz for spring constants of order 2 N/m with no tip attached. Though they can be operated without any additional tip by using an edge of the microcantilever,[10] one could hope for a better defined, sharper, and even more durable tip. If a tip of mass comparable to that of the microcantilevers could be placed on it, they could maintain their high resonant frequencies. In our hands, however, the smallest diamond that can now be mounted on these microcantilevers totally dominates the mass and reduces the resonant frequency to of order 10 kHz.

The double-wire cantilever is almost as robust as the double cross without suffering from its thermal instability. It is approximately one order of magnitude bigger than the SiO_2 microcantilever and hence is easier to work with and less fragile. It can have resonant frequencies of order 10 kHz for spring constants of order 10 N/m.

In summary, atomic force microscopy is brand new and exciting. A variety of designs give atomic resolution images. There are many opportunities for further design work with a goal of producing a force sensor with high lateral stability, good thermal stability, high resonant frequencies, and spring constants $\lesssim 10$ N/m. If this goal could be achieved, it would than be possible to make a robust and reliable microscope capable of nondestructively imaging a wide variety of samples including even some biological samples. It is easy to convert an AFM to STM for looking at conducting samples by replacing the force sensor of the AFM with a rigidly help tip.

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ACKNOWLEDGMENTS

We thank J. Schneir, J. Demuth, R. Hamers, P. Schoer, J. Becker, D. Smith, and C. F. Quate for their help with the computer image processing system; T. Albrecht for the gold plated tungsten wire and microcantilever; H. Ribi for the monolayer film; M. Wilson, R. Stuber, and K. Voelker for design help and microscope fabrication; E. Martzen and A. Dietler for secretarial help; D. Salisbury for help with the manuscript; J. Kotthaus, H. Kroemer, C. F. Quate, T. Albrecht, G. Binnig, R. Sonnenfeld, V. Elings, and S. Alexander for useful discussions. This work was supported in part by the Office of Naval Research (OM and BD), by the National Science Foundation Grant No. DMR 8613486 (SG), and by a grant from the Schweizerischer Nationalfonds zur Förderung der Wissenschaften (OM).

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